Magnetization reversals in a disk-shaped small magnet with an interface

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Abstract

We consider a nanodisk possessing two coupled materials with different ferromagnetic exchange constant. The common border line of the two media passes at the disk center dividing the system exactly in two similar semidisks. The vortex core motion crossing the interface is investigated with a simple description based on a two-dimensional model which mimics a very thin real material with such a line defect. The main result of this study is that, depending on the magnetic coupling which connects the media, the vortex core can be dramatically and repeatedly flipped from up to down and vice versa by the interface. This phenomenon produces burstlike emission of spin waves each time the switching process takes place.

PACS numbers: 75.75.+a; 75.60.Ch; 75.60.Jk
Keywords: vortices; Magnetic materials; vacancies.
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1 Introduction

The study of topological excitations is an important topic in modern theoretical and experimental physics. These objects are also related to technological applications in several branches of condensed matter physics such as superconductivity, superfluidity, magnetism, etc. For example, in micrometer-sized magnetic thin films, the magnetization typically adopts an in-plane circular configuration known as a magnetic vortex. At the vortex core, the magnetization turns sharply out of plane, pointing either up or down. Such a binary phenomenon generates the possibility of developing magnetic data storage but it would require the ability to flip the vortex core on demand. However, vortices are highly stable and therefore, very strong magnetic fields were previously thought to be necessary to accomplish this. Recently, it was shown that elaborated experiments with low fields (about 1.5 mT) can also reverse the direction of a vortex core [1].

On the other hand, the vortex-defect interaction is another mechanism with potential technological relevance. Really, point defects (holes) have been intentionally incorporated in magnetic nanodisks [2, 3, 4]. In these circumstances, the vortex-hole interactions lead to interesting effects [2, 3, 5, 6, 7, 8, 9, 10, 11]. Here, we would like to take into account another possible type of defect in the disk, which is more associated to a line defect. We will illustrate this in the case of a circular magnetic film having two media with different ferromagnetic exchange coupling constants A_α and A_β. Of course, these media are separated by an one-dimensional interface and the linking between them is achieved by a coupling constant $A_{\alpha\beta}$. A natural question to ask is what happens

to a magnetic vortex when its core encounters such inhomogeneities in the film. It is interesting because in thin or ultrathin ferromagnetic films, a large fraction of the magnetic moment bearing ions sit in interface or surface sites. These also can be affected by the chemical absorption of selected molecules. Hence we consider an interface (a line) passing exactly at the disk center and therefore, dividing the system in exactly two alike semidisks. Note that, in principle, such an arrangement could be built by joining two micrometer-size semidisks made of different ferromagnetic materials. Also, these different materials (with coupling constants A_α and A_β) could be suitably chosen as required by experimental observations and available systems. Such possibilities follow from the fact that the strength and character of magnetic anisotropies are subject to design (spin engineering). We would therefore expect that quasi-two-dimensional realizations of the above theoretical system can be made for experiments.

2 The model and results

To justify our model we remember that in ferromagnetic nanodisks or thin films, magnetostatic interactions usually induce the magnetization to lie parallel to their surfaces. Therefore, the magnetic moments will form rotationally symmetric patterns that follow closed flux lines. At the center, the tightly wound magnetization can not lie flat, because the short-range exchange interaction favors a parallel alignment of neighboring spins (magnetic moments). The direction of the out-of-plane spin component (up or down) defines the vortex core polarization. This configuration is the ground state and is known as vortex state. To reproduce these properties we consider a two-dimensional square lattice inside a circumference of radius R (in the xy-plane) possessing an "easy-plane anisotropy" on its surface (top or bottom). In addition, there is another kind of anisotropy on its circumferential border that tends to make the spins to point out along the tangent of the circumference envelop. These anisotropies imitate the magnetostatic effects. Thus, with the above considerations, a disk with an interface would be described by the following Hamiltonian

$$\begin{aligned} H &= -\sum_{r=\alpha,\beta} A_r \sum_{\{i,j\}\in r} \vec{\mu}_{i,r}\cdot\vec{\mu}_{j,r} - A_{\alpha\beta}\sum_k \vec{\mu}_{k,\alpha}\cdot\vec{\mu}_{k+1,\alpha} \\ &\quad + \sum_{\nu=1,2}\sum_l \delta_\nu(\vec{\mu}_l\cdot\hat{n}_{l,\nu})^2 - \sum_i \vec{h}\cdot\vec{\mu}_i, \end{aligned} \quad (1)$$

where $\vec{\mu}_i = \vec{M}_i(\vec{r})/M_s = \mu_i^x\hat{x} + \mu_i^y\hat{y} + \mu_i^z\hat{z}$ is the atomic moment (spin) unit vector at position i (M_s is the saturation magnetization) and $r = \alpha, \beta$ indicates the two media. In addition, $A_\alpha > 0$ and $A_\beta > 0$ are ferromagnetic couplings and the sum $\{i,j\} \in \alpha$ is over nearest-neighbor spins of medium α while the sum $\{i,j\} \in \beta$ considers only nearest-neighbor spins of medium β. All spins inside the film have coordination number of four but spins of both edge of the interface, interact only with three other spins of the same nature; the remaining interaction is with its nearest-neighbor of the other medium. This fact is included in the second term of Hamiltonian (1): the coupling between nearest-neighbor atoms belonging to different media is given by $A_{\alpha\beta} > 0$ and therefore, k indexes only magnetic moments belonging to the line interface at the side of medium α (hence, $k+1$ indexes only spins along the line interface at medium β). The third term mimics the magnetostatic energies and we will assume here that it does not depend on the media. Finally, the last term of the Hamiltonian considers the effects of an external magnetic field $\vec{h}$.

The third term ("magnetostatic energy") of Hamiltonian (1) is justified as follows: the sum over sites $\{l\}$ considers the scalar product of the local magnetic moments and the unitary vectors $\hat{n}_{l,\nu}$, which are perpendicular to either the circle plane ($\nu = 1$) or the circumference contour of the film ($\nu = 2$). In the present model, this contour is the lateral border of the disk. Therefore, the sum on ν forces the spins to preferentially become parallel to the film surface and circumferential contour line. For usual films (without defects, i.e., $A_\alpha = A_\beta = A_{\alpha\beta}$), the use of adequate values of the parameters can make the above model to qualitatively reproduce the vortex ground state and also, as will be seen below, it brings about the vortex core dynamics already obtained analytically

[12] and observed in experiments [13, 14, 15] as well as in micromagnetic simulations [12, 13, 14]. In principle, such a system could represent a very thin disk with thickness L and radius R so that its aspect ratio $L/R \ll 1$.

As it is well known, for usual films, the vortex structure can be set into a gyrotropic motion by application of a small magnetic field. This in-plane gyrotropic motion is the lowest excitation mode in elements exhibiting a vortex structure. The sense of gyration of the core in a circular trajectory (clockwise or counterclockwise) is determined only by the vortex core polarization. Because the sense of gyration determines the polarization, it is clear that a change in it unambiguously indicates a change in the vortex core polarization. Therefore, if the vortex core motion could be reflected in someway, its sense of gyration would be drastically changed and the polarization would be reversed. Here we show that such a mechanism could be naturally triggered by the existence of two different media separated by an interface inside the disk. Our study considers several values of the ratio $A_\beta/A_\alpha = \epsilon \leq 1$ with the parameter $A_{\alpha\beta}$ ranging from 0 to A_α.

The results are obtained by using spin dynamic simulations for spins occupying all possible points of a square lattice inside the circumference of radius R (in most simulations it was used $R = 20a, 25a$ and $30a$, where a is the lattice spacing). The Heisenberg equation of motion $d\vec{\mu}_i/dt = i[\vec{\mu}_i, H]$ is solved for each spin $\vec{\mu}_i$ interacting with its nearest neighbors. We have employed the fourth-order predictor-corrector method. In order to excite the lowest excitation mode (gyrotropic mode), a sinusoidal external magnetic field $\vec{h} = h_0\hat{x}\sin(\omega t)$ is applied for a short time (of the order of $700A_\alpha^{-1}$, which can be compared with the total time of the simulations $10^4 A_\alpha^{-1}$). The time increment is equal to $\Delta t = 0.0001A_\alpha^{-1}$. During all observations, the energy is conserved and the spin constraint $\vec{\mu}^2 = 1$ remains unaffected. In all calculations presented here the "magnetostatic" parameters are $\delta_1 = 0.2A_\alpha$ and $\delta_2 = 2A_\alpha$ (the disk size is $R = 20a$). The essential physics is not altered by other choices of the values of δ_1 if $0 < \delta_1 < 0.28$. For $\delta_1 > 0.28$, the vortex becomes essentially planar and does not develop the out-of-plane component at the core [16]. It is important to say that these selected relevant parameters for the disk (δ_1/A_α, δ_2/A_α) are reasonable for a material such as Permalloy (Py). To see this we carry out an estimate for a typical nanomagnet without defects ($A_\alpha = A_\beta = A_{\alpha\beta}$): in model (1), the exchange length l_0 can be written as $l_0 \approx a\sqrt{A_\alpha/\delta_1}$. For comparison with experimental results, $A_\alpha \equiv AL$, where $A \approx 1.3 \times 10^{-11} J/m$ is the exchange constant and the thickness L is on the order of $10^{-9}m$ for thin nanodisks made of Py, while $l_0 \approx \sqrt{A/\mu_0 M_s^2}$, with $M_s = 8.6 \times 10^5 A/m$ and $\mu_0 = 4\pi \times 10^{-7} N/A^2$. Therefore, we expect that $a\sqrt{A_\alpha/\delta_1} \sim \sqrt{A/\mu_0 M_s^2}$, which leads to $\delta_1/A_\alpha \approx \mu_0 M_s^2 a^2/A \sim 10^{-1}$. It is on the same order of the values used here. On the other hand, the range of δ_2/A_α was chosen to adequately obtain results about the vortex core dynamics comparable with the low-frequency gyrotropic mode, which lies in the GHz range. Really, combining the values δ_1/A_α and δ_2/A_α, we get a GHz frequency $\omega_G \sim 0.0056A_\alpha$ for the circular motion (gyrotropic mode) of the vortex core. Hence, for a disk with the above parameters and without defects, our results are in qualitatively and reasonably quantitatively agreement with experimental observations, particularly for $R = 20a \approx 20l_0 \approx 10^2 nm$.

Of course, we expect that a film containing two different coupled materials will exhibit distinct properties (see Figs.1 and 2 for visualization of a vortex in the system studied here). Our aim now is to know how a confined vortex experiences a line defect for some values of the parameters. Two situations resume the main possibilities. We start studying the case for $\epsilon = 0.9$, choosing $A_{\alpha\beta} = 0.8A_\alpha$ for the coupling between the media. The ground state is a vortex centralized out the disk center. Indeed, the equilibrium position was obtained using Monte Carlo calculations at low temperatures and, in this case, it is slightly displaced to the medium with smaller exchange constant (medium β) at position $\approx (a, 0)$. In general, this displacement increases as ϵ decreases. The sinusoidal field used to excite the gyrotropic mode has amplitude $0.0085A_\alpha$ and frequency $0.0089A_\alpha$. The results show clearly that the vortex core interacts with the interface and the gyrotropic mode becomes centralized in the medium with smaller exchange. In addition, when the core crosses the interface towards medium β, it speeds up (with respect to its velocity in the medium α) and when it goes from medium β to α the motion slows down. We also plot the average magnetization in the x and z directions $< \mu^x >$ and $< \mu^z >$ in Figs. 3 and 4 respectively. We notice that $< \mu^x >$

oscillates around zero indicating an almost circular motion and that the frequency of this "deformed gyrotropic mode" is $0.00377A_\alpha$, which is smaller than ω_G for a disk with the same size without defects. One may think in the possibility to use such "exotic" systems for the control of gyrotropic frequencies, which may be useful in technological applications. The analysis of the out-of-plane fluctuations is shown in Fig. 4. Note that $< \mu^z >$ oscillates very rapidly and with small amplitude around a small but finite positive value, indicating that the core is pointing up. These very small oscillations are essentially localized in the vortex core as it can be seen in Fig. 5, which shows the oscillations in μ^z averaged only over the core, rather than the whole disk. In this case, the amplitude is much larger than the one in Fig. 4 because much less spins are considered in the average. Such oscillations are induced by the discreteness of the lattice of the model adopted here. In fact, in its travel, the geometrical center of the vortex core alternates around points containing sites and vacancies: when it becomes centered on a site of the lattice, the average $< \mu^z >_{core}$ is larger due to the presence of a central spin in the core. On the other hand, when it moves away from the site (for example, in direction to the middle of a plaquette), the average decreases because there is no spin in the core center. We notice that $< \mu^z >_{core}$ oscillates around a value near 0.95. Since the small oscillation in $< \mu^z >$ is associated with discreteness effects, its Fourier transform does not reflect the main characteristics of the core motion. Indeed, there are two main peaks in its Fourier transform, which are not very different from that of the case free of defects. Figure 6 summarizes the main properties of the vortex motion showing the trajectory followed by the core during several laps.

No switching process is observed for these parameters. On the other hand, for $A_{\alpha\beta} = 0.5$, interesting phenomena take place. The vortex core equilibrium position is $\approx (a, 0)$ (see Figs. 1 and 2) for the $2D$ and $3D$ views of the system respectively) and it becomes completely confined in the medium β, even after starting its motion (induced by the sinusoidal field with amplitude $0.007A_\alpha$ and frequency $0.089A_\alpha$). Indeed, the core moves initially along a straight line (almost perpendicular to the interface) until a distance $d < R$ from the disk center and then it goes back to the interface not by the same path but following an approximate circular trajectory. However, arriving at the interface, the core is reflected by the line defect and consequently, a magnetization reversal takes place, causing a burstlike emission of spin waves. In sequence, the core goes back through almost the same circular trajectory until finding the interface again at diametrally opposite point, where it is reflected (and flipped) for a second time and so on (see Fig. 7 and supplementary Video of the vortex core dynamics as auxiliary material [17]). Therefore, only a semi-circular mode is observed. Indeed, the core tries to develop a complete gyrotropic motion (see also Figs. 8 and 9), but it is impeded by the interface. The Fourier transform of $< \mu^x >$ has a main peak at frequency $0.0039A_\alpha$, while for $< \mu^y >$ the main peak occurs at frequency $0.0081A_\alpha$. Hence, the motion becomes very irregular. The amplitude of the vortex motion decreases as this process is repeated and the vortex center speeds up leading to rapid changes in the directions of motion and the subsequent phenomenon in which the core magnetization changes coherently up and down. The core approaches more and more the defect and eventually it becomes trapped, oscillating along the straight line of the interface alike an one-dimensional damped harmonic motion with frequency $0.027A_\alpha$. Of course, this additional frequency is present only in the Fourier transform of $< \mu^x >$, since the vortex center now oscillates only along the interface (y-axis). All these up-down, down-up sequences are really intense occurring surrounded by a "sea" of spin waves, which are all the time perturbing the vortex core. These dramatic and sudden switching processes are caused by the competition between magnetostatic interactions and the strong discontinuity in the exchange interaction along the interface. These are truly exchange explosions and spin wave fluctuations are strongly produced. Such phenomenon may provide further insights for generating and controlling spin waves in magnetic nanodisks.

In order to see more details about this switching mechanism, we have also plotted the average magnetization along the z-direction $< \mu^z >$ in Fig. 10. It can be easily observed that, initially, $< \mu^z >$ alternates its rapid oscillations between very small positive and negative values. As already discussed earlier, the mechanism of this effect is the sequential magnetization reversals of the vortex core due its interactions with the line defect. This effect remains until $t \sim 5500A_\alpha^{-1}$.

After that, the out-of-plane magnetization oscillates still more rapid around zero. This characterizes the capture process of the core by the interface; although the vortex center oscillates along the line defect, its out-of-plane core is almost lost. Really, it seems that after being captured by the interface, the vortex center still remains oscillating with some reversal.

3 Conclusions and prospects

Magnetization switching is a remarkable effect observed in a broad range of magnetic materials. Here, we have presented a study of how a defect along a line separating two magnetic media may induce polarization reversal in vortex-like magnetization lying on nanomagnets. Using Hamiltonian (1) we have studied the vortex core interactions with the line defect in confined magnetic systems. In the absence of defects, the results obtained by this model agree qualitatively with experimental observations. Therefore, it is sound natural to expect that we can be able to predict still unobserved facts and possibilities for disks possessing defects and other characteristics.

As discussed before, a change in the sense of gyration of the vortex structure is an unambiguous indication of a switching of the vortex core polarization. So, we have predicted a sequential switching process induced by vortex-interface interactions. Indeed, for $\epsilon = 0.9$ and $A_{\alpha\beta}$ not so large, we easily observe that every time the core is reflected by the interface, the magnetization reversal happens [17]. It prevails for some time interval and eventually, the core becomes captured by the defect. After being captured, the vortex core appears to oscillate forward-backward along the line defect, reversing its remaining polarization (which is much smaller than before its capture, as it can be seen in video [17]. During these oscillations, a considerable amount of spin waves is emitted, mainly when the core reversals take place. Such bursts of spin waves propagate throughout the system, interacting and disturbing the magnetization dynamics as a whole. Reaching the disk border, such waves are reflected back, so that larger and lager amount of spin waves occupies the system. Eventually, the vortex dynamics runs out once all its kinetic energy were dissipated. Therefore, our original proposal of investigating the effects of a line on vortex dynamics seems to be also very useful to produce such waves and study their properties in confined structures.

In summary, we have investigated the vortex core dynamics in magnetic nanodisks with a line defect. Our model predicts remarkable switching process which may be useful for technological applications such as those which utilize vortex degrees of freedom, namely, its polarization and mechanisms associated to its reversal. Very recently, such a phenomenon has been observed experimentally [18] and in simulations [19, 20] in nanomagnets with artificial holes. As prospects for future investigations, we may quote the use of line defects to divide a magnetic sample in several islands separated by such interfaces. For instance, whenever one can set up a vortex in each island, one can produce an array with possible interesting interactions between vortices located at neighbor islands. Perhaps, a global control of vortex properties (polarization, chirality, etc) could be attainable by means of such interactions.

The authors thank CNPq, FAPEMIG and CAPES (Brazilian agencies) for financial support.

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[17] Auxiliary video, clearly showing the vortex core motion interacting with the interface and subsequent switching processes, is available under request: ricardodasilva@ufv.br, apereira@ufv.br, or winder@ufv.br .

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Figure Captions

Fig. 1 (Color online) Top view of a nanodisk with an interface along the y-axis. The two sides of the disk are made of different materials (here, black with exchange coupling A_α and red with A_β) and are joined by an inter-side coupling $A_{\alpha\beta}$. The vortex core equilibrium position is located at the medium with smaller exchange constant (red medium).

Fig. 2 (Color online) Three-dimensional view of a disk with an interface. The vortex core can be seen in its equilibrium position pointing "up" in the medium with smaller exchange constant A_β. The application of an external field induces the gyrotropic mode. As the core tries to cross the interface, it can experience several effects, depending on A_β and $A_{\alpha\beta}$.

Fig. 3 The average magnetization in the x-direction $< \mu^x >$ and its Fourier transform for $\epsilon = 0.9$ and $A_{\alpha\beta} = 0.8A_\alpha$. The same behavior is verified for the y-component of the average magnetization (not shown).

Fig. 4 The average magnetization in the z-direction $< \mu^z >$ and its Fourier transform for $\epsilon = 0.9$ and $A_{\alpha\beta} = 0.8A_\alpha$.

Fig. 5 The average magnetization in the z-direction over the vortex core $< \mu^z >_{core}$ for $\epsilon = 0.9$ and $A_{\alpha\beta} = 0.8A_\alpha$.

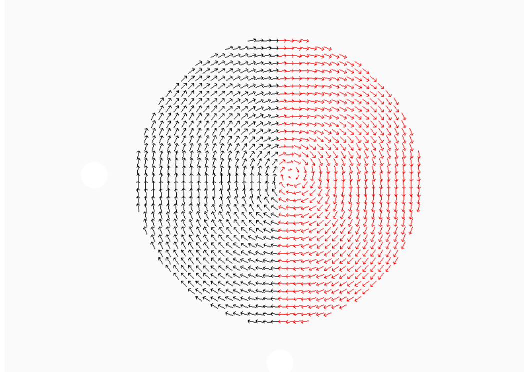
Fig. 6 The gyrotropic motion of the vortex core in a nanodisk with an interface for $\epsilon = 0.9$ and $A_{\alpha\beta} = 0.8A_\alpha$. The disk center is placed at $(20a, 20a)$ and the dashed line is along the defect. Like in Fig. 1, media α and β are the left and right parts of the disk, respectively. Note that the path of the core is larger in medium β.

Fig. 7 (Color online) Vortex core motion in the disk with an interface ($\epsilon = 0.9, A_{\alpha\beta} = 0.5A_\alpha$). The center of the disk is placed at $(20a, 20a)$ and, therefore, this figure shows only the right part of the disk. In fact, for this case, the vortex core becomes confined in the medium β. Black arrows indicate the counterclockwise gyration while the red ones indicate the clockwise.

Fig. 8 The average magnetization in the x-direction $< \mu^x >$ and its Fourier transform for $\epsilon = 0.9$ and $A_{\alpha\beta} = 0.5A_\alpha$. Initially, the vortex core moves along trajectories that resemble semi-circumferences until being captured by the defect.

Fig. 9 The average magnetization in the y-direction $< \mu^y >$ and its Fourier transform for $\epsilon = 0.9$ and $A_{\alpha\beta} = 0.5A_\alpha$.

Fig. 10 The average magnetization in the z-direction $< \mu^z >$ and its Fourier transform for $\epsilon = 0.9$ and $A_{\alpha\beta} = 0.5A_\alpha$. Note the cyclic switching processes until the capture around $t = 5500A_\alpha^{-1}$.



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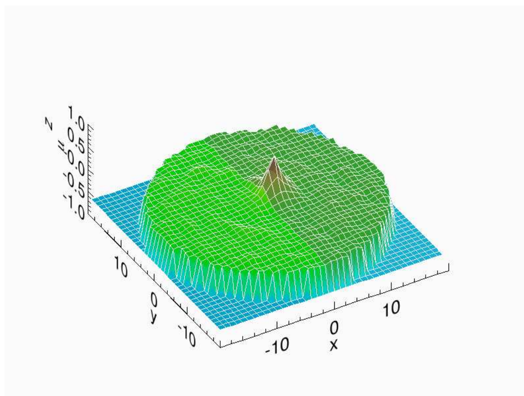

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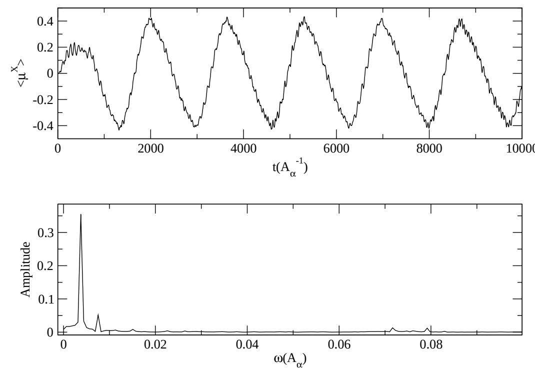

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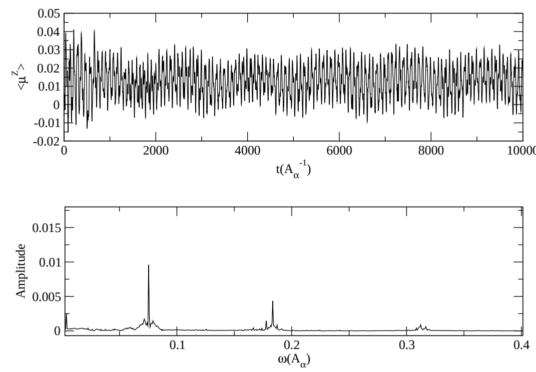

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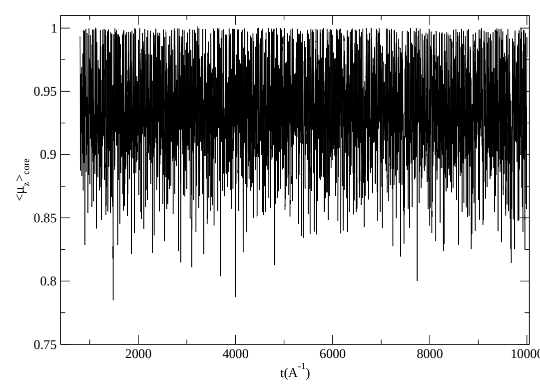

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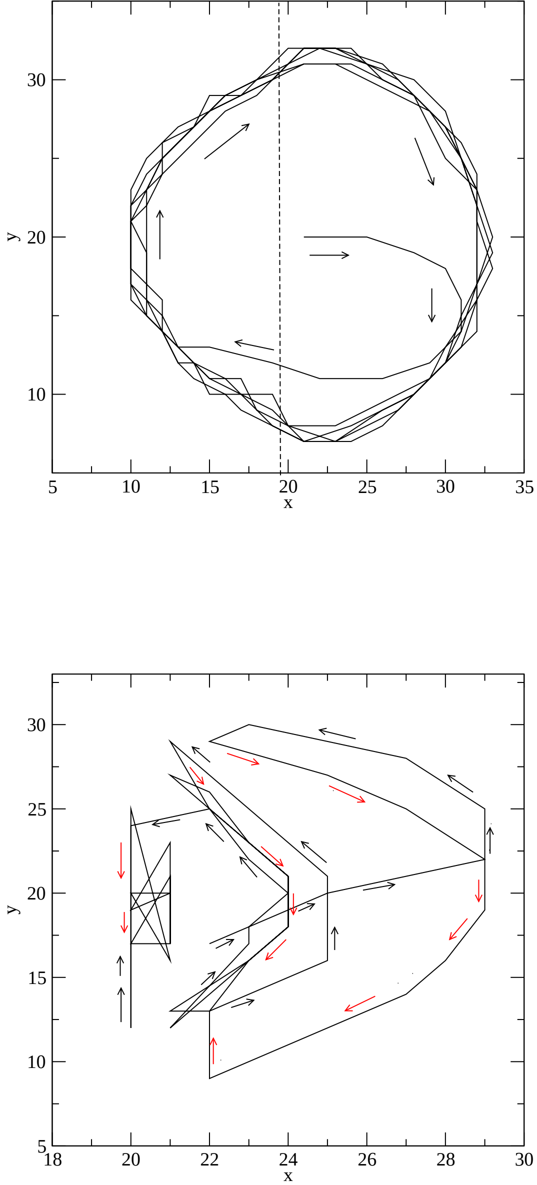

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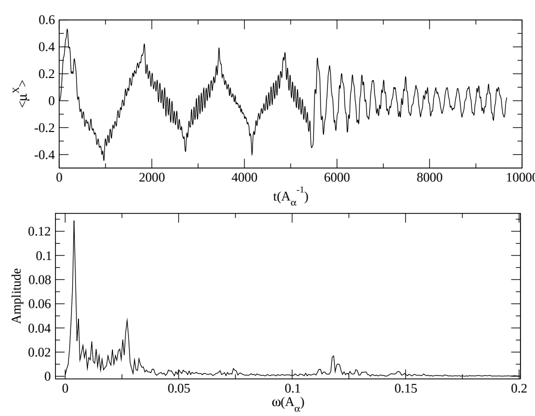
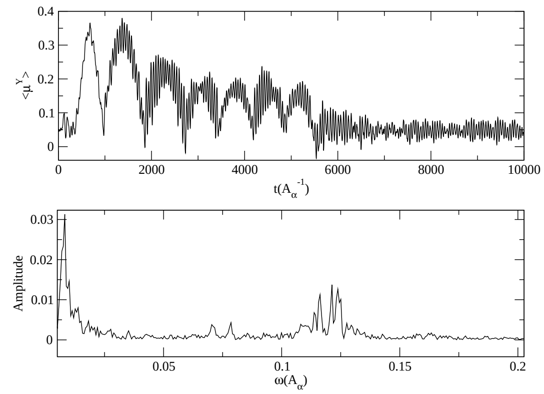


Figure 8:



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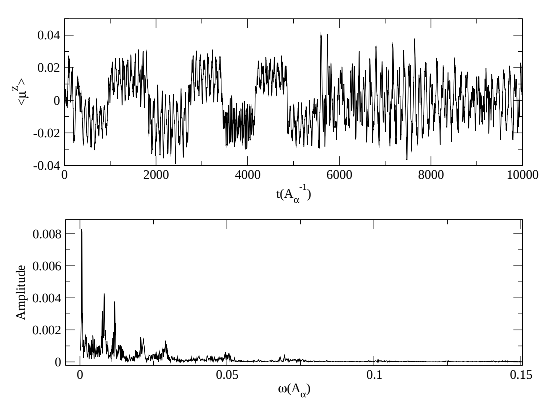

Figure 10: